Measurement of the underlying event activity using charged-particle jets in proton-proton collisions at $\sqrt{s} = 2.76$ TeV

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Measurement of the underlying event activity using charged-particle jets in proton-proton collisions at $\sqrt{s} = 2.76$ TeV

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Abstract: A measurement of the underlying event (UE) activity in proton-proton collisions is performed using events with charged-particle jets produced in the central pseudorapidity region ($|\eta^{\text{jet}}| < 2$) and with transverse momentum $1 \leq p_{\mathrm{T}}^{\text{jet}} < 100\,\text{GeV}$. The analysis uses a data sample collected at a centre-of-mass energy of 2.76 TeV with the CMS experiment at the LHC. The UE activity is measured as a function of $p_{\mathrm{T}}^{\text{jet}}$ in terms of the average multiplicity and scalar sum of transverse momenta (p_{T}) of charged particles, with $|\eta| < 2$ and $p_{\mathrm{T}} > 0.5\,\text{GeV}$, in the azimuthal region transverse to the highest p_{T} jet direction. By further dividing the transverse region into two regions of smaller and larger activity, various components of the UE activity are separated. The measurements are compared to previous results at 0.9 and 7 TeV, and to predictions of several Monte Carlo event generators, providing constraints on the modelling of the UE dynamics.

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1 Introduction

Hadron production in high-energy proton-proton (pp) collisions originates from multiple scatterings of the partonic constituents of the protons at central rapidities, and from "spectator" (noncolliding) partons emitted in the very forward direction. The produced partons reduce their virtuality through gluon radiation and quark-antiquark splittings, and finally fragment into hadrons at scales approaching 0.2 GeV (Λ_{QCD}). Usually, one separates the produced hadrons into two classes: those coming directly from the fragmentation of partons resulting from the scattering with the largest momentum transfer (hard scattering) in the event, and the rest (underlying event, or UE). The UE thus consists of hadrons coming from (i) initial- and final-state radiation (ISR, FSR) from the hard scattering, (ii) softer partonic scatters in the same pp collision (multiple parton interactions, or MPI) possibly with their own initial- and final-state radiation, and (iii) proton remnants concentrated along the beam direction.

An accurate understanding of the UE is required for precise measurements of standard model processes at high energies and searches for new physics. Indeed, the UE affects measurements of isolated high transverse momentum p_{T} leptons or photons, and it dominates most of the hadronic activity from the overlapping pp collisions taking place in a given bunch crossing (pileup) at the high luminosities achieved by the CERN LHC. The semi-hard and low-momentum partonic processes, which dominate the UE, cannot be adequately calculated with perturbative Quantum Chromodynamics (pQCD) methods alone, and require a phenomenological description containing parameters that must be tuned to data.

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The topological structure of pp interactions with a hard scattering can be used to define experimental observables sensitive to the UE. One example is the study of particle properties in regions away from the direction of the products of the hard scattering. At the Tevatron, the CDF experiment measured UE observables using inclusive jet and Drell-Yan (DY) events in $p\bar{p}$ collisions at centre-of-mass energies $\sqrt{s} = 0.63$, 1.8, and 1.96 TeV [1–3]. In pp collisions at the LHC, the ALICE, ATLAS, and CMS experiments have carried out UE measurements at $\sqrt{s} = 0.9$ and 7 TeV using events containing a leading (highest p_T) charged-particle jet [4–6] or a leading charged particle [7, 8], or a DY lepton pair [9]. In this paper, we study the UE activity in pp collisions at $\sqrt{s} = 2.76$ TeV by measuring the average multiplicity and scalar transverse momentum sum (Σp_T) densities of charged particles in the azimuthal region orthogonal to the direction of the leading charged-particle jet, referred to as the transverse region.

At a given centre-of-mass energy, the UE activity is expected to increase with the momentum transfer between the interacting partons (hard scale). On average, increasingly hard parton interactions result from pp collisions with decreasing impact parameters between the two protons, which in turn enhance the overall hadronic activity originating from MPI until a saturation is reached for central collisions with maximum overlap [10, 11]. At the same time, the activity related to the ISR and FSR components also increases with the hard scale. For events with the same hard scale, probed by the p_T of jets or DY pairs, the MPI activity rises with $\sqrt{s}$, as more partons are expected in the protons at increasingly smaller parton fractional momenta $x \sim 2\,p_T/\sqrt{s}$ [10, 11]. Hence, studying the UE as a function of the hard scale at several centre-of-mass energies provides an insight into the UE dynamics and its evolution with the collision energy, further constraining the model parameters.

The paper is organised as follows. Section 2 presents the main features of the Monte Carlo (MC) event generators used in this study to provide a description of the UE properties. Section 3 briefly describes the experimental methods, observables, event and track selection, as well as the corrections and systematic uncertainties of the measurements. The results are presented in section 4, and summarised in section 5.

2 Monte Carlo event generators

In this analysis, the PYTHIA6 [12], PYTHIA8 [13], and HERWIG++ [14] MC event generators are used with various tunes that are described below. In PYTHIA, the 2→2 parton scatterings, including MPI, are described by leading-order pQCD, with the $1/p_T^4$ cross section divergence regularised by introducing a low-p_T infrared cutoff (p_{T0}), such that the diverging term is replaced by $1/(p_T^2 + p_{T0}^2)^2$. There are various tunable parameters that control the behaviour of this regularisation, the matter distribution of partons in the transverse plane within the hadrons, and the final-state colour reconnection effects among the produced partons. When QCD radiation is modelled via a p_T-ordered evolution, the MPI and parton showers are interleaved in one common sequence of decreasing p_T values [15]. For the latest version of PYTHIA6 only ISR showers and MPI are interleaved, while in PYTHIA8 FSR showers are also included. The final nonperturbative transition of partons to hadrons is described by the Lund string fragmentation model [16].

Another general-purpose generator, HERWIG++, is similar to PYTHIA, but uses angular-ordered parton showers and the cluster model [14] for hadronisation. It has an MPI model similar to the one used by PYTHIA, with tunable parameters for regularising the partonic cross sections at low momentum transfer, but does not include the interleaved evolution with ISR and FSR.

Both MC models incorporate multiple parton collisions "perturbatively" — i.e. based on a "regularisation" of the underlying pQCD subprocesses' cross sections — but require a nonperturbative ansatz for the impact parameter profile of the colliding protons. The frequency of MPI is then generated by assuming a Poissonian distribution of the number of elementary partonic interactions over the overlapping pp volume, with the average number depending on the impact parameter of the hadronic collision [10, 11]. The MPI cross section is dominated by scatterings with semi-hard momentum transfers, O(1–2 GeV), involving low-x partons, and thus shows a stronger dependence on the evolution of the low-p_{T} infrared cutoff, and on the incoming parton densities than the single hard-scattering interactions [10, 11]. In PYTHIA6, PYTHIA8 and HERWIG++, the energy dependence of MPI is mostly controlled by the energy evolution of the low-p_{T} infrared cutoff parameter ,which follows a (tunable) power law dependence on the centre-of-mass energy [12–14]. The UE activity accompanying various types of hard scattering processes is well described by MC event generators, [4, 5, 7–9], illustrating the universality of MPI in different event topologies and hard-scattering production processes. Such a universality is confirmed by the similarity between the UE activity measured in DY [9] and jet-dominated events [4, 5, 7, 8], despite their different underlying parton radiation patterns.

In this analysis, several event generator tunes are used. These are the PYTHIA6 (version 6.426 [12]) tunes Z2, Z2*, and CUETP6S1 [17], PYTHIA8 (version 8.175 [13]) tunes 4C [18] and CUETP8S1 [17], and HERWIG++ 2.7 with tune UE-EE-5C [14, 19]. All of these tunes use the CTEQ6L1 [20] parton density function. The energy dependence of p_{T0} in these tunes is parameterised as $p_{\mathrm{T0}}(\sqrt{s}) = p_{\mathrm{T0}}^{\mathrm{REF}} \times (\sqrt{s}/E_0)^{\epsilon}$, where $p_{\mathrm{T0}}^{\mathrm{REF}}$, E_0, and ϵ are tune parameters summarised in table 1. These parameters were obtained by tuning to different data sets. The 4C tune was derived from early LHC data on charged particle multiplicities [18]. Z2, Z2*, CUETP6S1 and CUETP8S1 were tuned to the previous UE results from CMS at 0.9 and 7 TeV [5]. In addition, CUETP6S1 tune also included CDF data [21] at 0.3, 0.9, and 1.96 TeV, while CUETP8S1 tune used 0.9 and 1.96 TeV data for tuning. The UE-EE-5C was tuned with the ATLAS UE data at 0.9 and 7 TeV [7] and CDF UE data at 0.3, 0.9, and 1.96 TeV [21]. None of the tunes make use of data at 2.76 TeV, making this a good test of interpolation between other centre-of-mass energies. The detector response was simulated in detail by using the GEANT4 package [22], and simulated events were processed and reconstructed in the same manner as collision data.

3 Experimental methods

3.1 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume there are several

Tune	$p_{\mathrm{T0}}^{\mathrm{REF}}$ (GeV)	E_0 (GeV)	ϵ
Z2	1.832	1800	0.275
Z2*	1.921	1800	0.227
CUETP6S1	1.9096	1800	0.2479
4C	2.085	1800	0.19
CUETP8S1	2.1006	1800	0.2106
UE-EE-5C	3.91	7000	0.33

Table 1. Summary of the parameters of the Monte Carlo generator tunes.

complementary detectors: a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. The silicon tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$. For non-isolated particles of $1 < p_{\mathrm{T}} < 10\,\mathrm{GeV}$ and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_{T}, and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [23]. Two of the CMS subdetectors acting as LHC beam monitors, the Beam Scintillation Counters (BSC) and the Beam Pick-up Timing for the eXperiments (BPTX) devices, are used to trigger the detector readout. The BSC are located along the beam line on each side of the Interaction Point (IP) at a distance of 10.86 m and cover the range $3.23 < |\eta| < 4.65$. The two BPTX devices, located inside the beam pipe at distances of 175 m from the IP, are designed to provide precise information on the bunch structure and timing of the incoming beams, with a time resolution better than 0.2 ns. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [24].

3.2 Event and track selection

The present analysis is performed with a data sample of proton-proton collisions collected with the CMS detector at $\sqrt{s} = 2.76\,\mathrm{TeV}$ during a dedicated run in March 2011, corresponding to an integrated luminosity of $0.3\,\mathrm{nb}^{-1}$. In 6.2% of the events there is an extra (pileup) pp collision, corresponding to an average of 0.12 overlapping pp collisions. Minimum bias events were recorded by requiring activity in both BSC counters in coincidence with signals from both BPTX devices (in contrast to ref. [5], where only one of the BPTX devices is required). To reduce the statistical uncertainty for the highly prescaled minimum bias trigger at large $p_{\mathrm{T}}^{\mathrm{jet}}$, single-jet triggers based on information from the calorimeters, with p_{T} thresholds at 20 and 40 GeV, were also used to collect data (differently from ref. [5], where thresholds of 30 and 50 GeV are used). Events identified as originating from beam-halo background were removed from the sample [25]. The event selection requires exactly one primary vertex with more than four degrees of freedom (approximately 4 particles) and located no more than ± 10 cm from the centre of the luminous region (beamspot) in the z-direction.

For each selected event, the reconstructed track collection needs to be freed from undesired tracks, namely secondaries and background from track combinatorics and beam halo tracks. Tracks not corresponding to actual charged particles (misreconstructed tracks) are suppressed by imposing the *high-purity* selection criteria [23]. Secondary decays are suppressed by requiring that the impact parameter significance $d_0/\sigma(d_0)$ (measure of the distance between the track and the primary vertex in the xy-plane) and the significance in the z-direction $d_z/\sigma(d_z)$ to be each less than 3. In order to remove tracks with poor momentum measurement, we require the relative uncertainty in the momentum measurement $\sigma(p_\mathrm{T})/p_\mathrm{T}$ to be less than 5%. The average reconstruction efficiency for the selected tracks is about 85% and drops to 75% for tracks with $p_\mathrm{T} \approx 0.5\,\mathrm{GeV}$ and $|\eta| \approx 2$, while the track misreconstruction rate is about 2%, increasing to about 8% for tracks with $p_\mathrm{T} \approx 0.5\,\mathrm{GeV}$ and $|\eta| \approx 2$. Track efficiencies are determined by matching the generated level and reconstructed level tracks.

The event hard scale and reference direction, for the identification of the UE sensitive region, are defined using leading "track jets" [26] or charged-particle jets. The use of track jets makes the transition of leading tracks to leading jets more continuous and extends the p_T coverage to larger values. These jets are reconstructed from tracks with $p_\mathrm{T} > 0.5\,\mathrm{GeV}$ and $|\eta| < 2.5$ using the Seedless Infrared-Safe Cone (SISCone) [27] algorithm with distance parameter of 0.5. Although anti-k_T [28] is now the preferred algorithm at the LHC, the SISCone algorithm is chosen in this analysis for compatibility with previous results [5]. Furthermore, a comparison of the UE activity obtained at generator level using SISCone and anti-k_T algorithms has been performed, finding differences of only a few percent for $p_\mathrm{T}^\mathrm{jet} \leq 20\,\mathrm{GeV}$. From all reconstructed track jets with $|\eta| < 2$ and $p_\mathrm{T} > 1.0\,\mathrm{GeV}$, the one with the largest $p_\mathrm{T}^\mathrm{jet}$ is selected. Only events containing at least one track jet fulfilling these criteria are considered for this analysis. Jets are reconstructed with a matching efficiency of 80% at $p_\mathrm{T}^\mathrm{jet} \approx 1\,\mathrm{GeV}$ and up to 95% for $p_\mathrm{T}^\mathrm{jet} > 20\,\mathrm{GeV}$. Trigger conditions are chosen to keep the trigger efficiency as uniform as possible and close to 100%. For the $p_\mathrm{T}^\mathrm{jet}$ ranges in [1, 25), [25, 50), and [50, 100) GeV, we use the minimum-bias and the two single-jet samples, respectively, corresponding to about 11M, 50k, and 23k selected events.

3.3 Observables

In this analysis we follow the same methodology as in the previous studies of the UE activity in events with a leading charged-particle jet, carried out at $\sqrt{s} = 0.9$ and $7\,\mathrm{TeV}$ [5]. Charged-particle jets and charged particles produced at central pseudorapidity ($|\eta| < 2$) with $p_\mathrm{T} > 1$ and $0.5\,\mathrm{GeV}$, respectively, are used to study the UE properties. The direction of the leading charged-particle jet in the event is used to select charged particles in the transverse region defined by $60^\circ < |\Delta\phi| < 120^\circ$, where $\Delta\phi$ is the relative azimuthal distance between a charged particle and the leading jet. The UE is measured in terms of particle and Σp_T densities, as a function of the leading $p_\mathrm{T}^\mathrm{jet}$, which is used as an estimate for the hard scale of the interaction. The particle density ($\langle N_\mathrm{ch}\rangle \,/\, [\Delta\eta\Delta(\Delta\phi)]$) and Σp_T density ($\langle \sum p_\mathrm{T}\rangle \,/\, [\Delta\eta\Delta(\Delta\phi)]$) are computed, respectively, as the average number of primary charged particles, and the average of their scalar p_T sum, each per unit of η and of $\Delta\phi$.

As suggested in ref. [29], the transverse region can be studied in detail by separating — independently for the particle multiplicity and for the p_{T} sum — the $60^\circ < \Delta\phi < 120^\circ$ and the $-120^\circ < \Delta\phi < -60^\circ$ ranges, and identifying the regions with higher and lower activities, referred to as transMAX and transMIN, respectively. The two regions should have roughly equal activities for most events since the dominant production channel, two-jet production, is topologically symmetrical. In a three-jet topology, the transMAX side will capture the activity from the third jet. The difference between the measured densities in the transMAX and transMIN regions is called the transDIF density. The resulting particle and Σp_{T} densities are expected to be sensitive to different components of the UE activity.

Since the transMAX region contains the third jet, while both transMAX and transMIN regions receive contributions from MPI and beam remnants, the transMIN activity is sensitive to MPI and beam remnants, and the transDIF activity is sensitive to harder initial- and final-state radiation. The present approach extends the methodology employed in ref. [5]

3.4 Corrections and systematic uncertainties

The UE observables ($\langle N_{\mathrm{ch}} \rangle / [\Delta\eta\Delta(\Delta\phi)]$ and $\langle \sum p_{\mathrm{T}} \rangle / [\Delta\eta\Delta(\Delta\phi)]$) described in section 3.3 are reconstructed from selected tracks, with $p_{\mathrm{T}} > 0.5\,\mathrm{GeV}$ and $|\eta| < 2$, in the region transverse to the leading track-jet. These measured observables are corrected for detector effects and selection efficiencies to reflect the primary charged-particle activity using a 2-dimensional, iterative unfolding technique [30] based on response matrices that correlate the generated and reconstructed level observables. These matrices are constructed from the generator level and reconstructed level UE and $p_{\mathrm{T}}^{\mathrm{jet}}$ observables for PYTHIA6 Z2 events; this procedure accounts for detector effects and inefficiencies. The unfolding matrices are applied to a PYTHIA8 4C sample to estimate the systematic uncertainties related to the correction procedure. These vary between 0.2% and 4%, depending on the observable, region and $p_{\mathrm{T}}^{\mathrm{jet}}$.

Several other sources of systematic uncertainties may affect the results. These include the implementation of the simulation of the track and vertex selection criteria, tracker alignment and material content, background contamination, trigger conditions, and pileup contributions. The uncertainty in the simulation of the track selection is evaluated by applying various sets of selection criteria and comparing their effects on the data and on the simulated events. The impact parameter significance ranges are varied by one unit around the nominal window resulting in an effect on the densities of 0.6–4%. Replacing the *high-purity* selection by the simpler requirement $N_{\mathrm{layers}} \geq 4$ and $N_{\mathrm{pixel\ layers}} \geq 2$ for the silicon strip and pixel detector layers, respectively, has an effect of up to 0.8%. Varying the fraction of misreconstructed tracks by 50% affects the densities by 0.4–0.6%. The description of inactive tracker material in the simulation is adequate within 5% [4], and increasing the material densities by 5% in the simulation induces a change in the observables of 1%. The effects of tracker misalignment, precision in the IP position, and dead channels, evaluated by varying the detector conditions in the MC simulation, are each found to change the results by 0.1–0.3%. The effect of varying the trigger and vertex efficiencies within their uncertainties, as well as the effect of pileup contributions, all lead to a negligible effect.

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Source	Systematic (%)
Unfolding procedure	0.2–4
Impact parameter significance	0.6–4
Fraction of misreconstructed tracks	0.4–0.6
Track selection	0.1–0.8
Material density	1
Dead channels	0.1
Tracker alignment	0.2–0.3
Interaction point position	0.2
Total	1.9–5.8

Table 2. Summary of the systematic uncertainties (in percentage) due to various sources. The values range from the minimum to maximum from all regions, observables, and across different $p_{\mathrm{T}}^{\mathrm{jet}}$ values.

Systematic uncertainties are largely independent of one another, but they are correlated among data points in each experimental distribution. They are added in quadrature to the statistical uncertainties and are shown in all figures. Systematic uncertainties mostly dominate the statistical ones, which are often smaller than the data points. Table 2 shows a summary of the systematic uncertainties as a range from the minimum to maximum values as they vary across region, observable and $p_{\mathrm{T}}^{\mathrm{jet}}$. The transMAX and transMIN regions tend to have a larger total systematic uncertainty than the other regions and the $\langle\sum p_{\mathrm{T}}\rangle\,/\,[\Delta\eta\Delta(\Delta\phi)]$ observable tends to have a slightly larger total systematic uncertainty by about 0.2% compared to the $\langle N_{\mathrm{ch}}\rangle\,/\,[\Delta\eta\Delta(\Delta\phi)]$observable. The total systematic uncertainty is large at low $p_{\mathrm{T}}^{\mathrm{jet}}$ and decreases to a minimum at $p_{\mathrm{T}}^{\mathrm{jet}} \approx 3\,\mathrm{GeV}$ and then rises again up to a plateau for $p_{\mathrm{T}}^{\mathrm{jet}} > 20\,\mathrm{GeV}$.

4 Results

In figure 1, the (a) particle and (b) Σp_{T} densities, after unfolding, are shown in the transverse region, relative to the leading charged-particle jet, as a function of $p_{\mathrm{T}}^{\mathrm{jet}}$. A steep rise of the underlying event activity in the transverse region is seen up to $p_{\mathrm{T}}^{\mathrm{jet}} \approx 8\,\mathrm{GeV}$, followed by a "saturation" (plateau-like) region, with nearly constant multiplicity and small Σp_{T} density increase. In figure 2, the (left panes) particle and (right panes) Σp_{T} densities after unfolding are shown as a function of $p_{\mathrm{T}}^{\mathrm{jet}}$ in the transverse region with maximum and minimum activities (transMAX and transMIN), respectively. In the transMIN region, the amount of UE activity is roughly half that in the transMAX region. The $p_{\mathrm{T}}^{\mathrm{jet}}$ dependences observed in the two regions are also quite different. At high p_{T}, the distributions show a slow rise in the transMAX region, while for transMIN the flattening of the UE activity as a function of $p_{\mathrm{T}}^{\mathrm{jet}}$ is more pronounced. The corresponding distributions in the difference

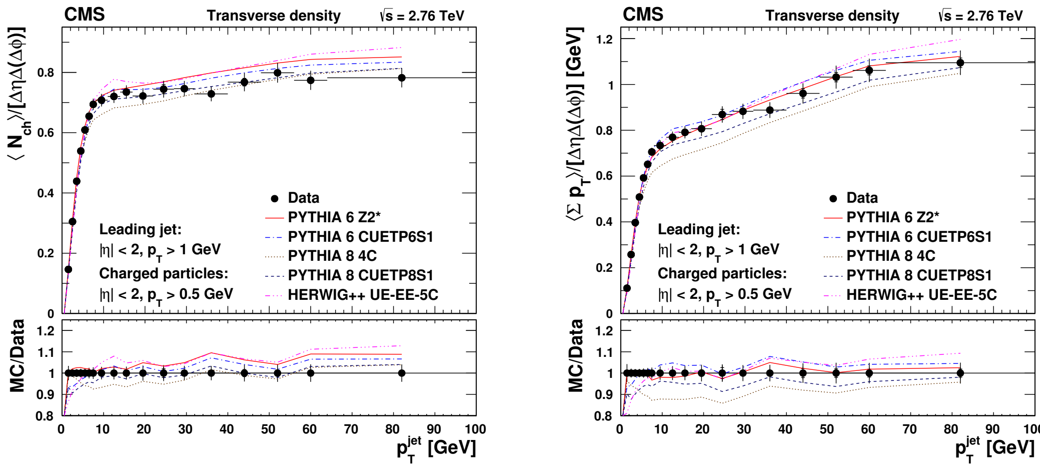

Figure 1. Measured (left) particle density, and (right) Σp_{T} density, in the transverse region relative to the leading charged-particle jet in the event ($|\eta| < 2$, $60° < |\Delta\varphi| < 120°$), as a function $p_{\mathrm{T}}^{\mathrm{jet}}$. The data (symbols) are compared to various MC simulations (curves). The ratios of MC simulations to the measurements are shown in the bottom panels. The inner error bars correspond to the statistical uncertainties, and the outer error bars represent the statistical and systematic uncertainties added in quadrature.

between the transMAX and transMIN regions (transDIF) are presented in figure 3. The particle and Σp_{T} densities both show a rise with $p_{\mathrm{T}}^{\mathrm{jet}}$, and the plateau-like region above $p_{\mathrm{T}}^{\mathrm{jet}} \approx 8\,\mathrm{GeV}$— seen for distributions in the individual transMAX and transMIN regions — is replaced by an increase as a function of $p_{\mathrm{T}}^{\mathrm{jet}}$.

The rapid increase of the UE activity with $p_{\mathrm{T}}^{\mathrm{jet}}$ in the region below $\sim 8\,\mathrm{GeV}$ is mainly attributed to the increase of MPI activity as the hard scale of the interaction increases [11]. This fast rise is followed by a saturation region (for the transverse and especially transMIN distributions), with nearly constant multiplicity and small Σp_{T} density increase. This behaviour is expected as a consequence of a nearly full overlap of the colliding protons in interactions yielding the hardest parton-parton scatterings. When pp collisions occur for very small impact parameter, the amount of MPI activity saturates [10, 11]. Such a distinct $p_{\mathrm{T}}^{\mathrm{jet}}$-dependent pattern in the amount of UE activity (sharp rise followed by a plateau above the $p_{\mathrm{T}}^{\mathrm{jet}} \approx 8\,\mathrm{GeV}$ transition) is clearly seen for all the observables presented, especially in the transMIN region. In contrast, the transMAX and transDIF distributions show a continuous rise with $p_{\mathrm{T}}^{\mathrm{jet}}$ also in the high-p_{T} regime. This is expected to be caused by contributions from initial- and final-state radiation in the transverse region [29]. Following such an interpretation, the present results provide constraints on the modelling of the different UE components.

The results are compared to recent tunes of the PYTHIA and HERWIG++ event generators. All PYTHIA6 and PYTHIA8 tunes predict the distinctive change in the amount of activity as a function of the leading jet p_{T} within 5–10%. The HERWIG++ UE-EE-5C tune also provides a fair description of the data. In general, the data-model agreement improves for the transDIF densities. The continuous increase observed at high-$p_{\mathrm{T}}^{\mathrm{jet}}$ in the transDIF distributions is well reproduced by all MC tunes, corroborating the hypothesis of increased

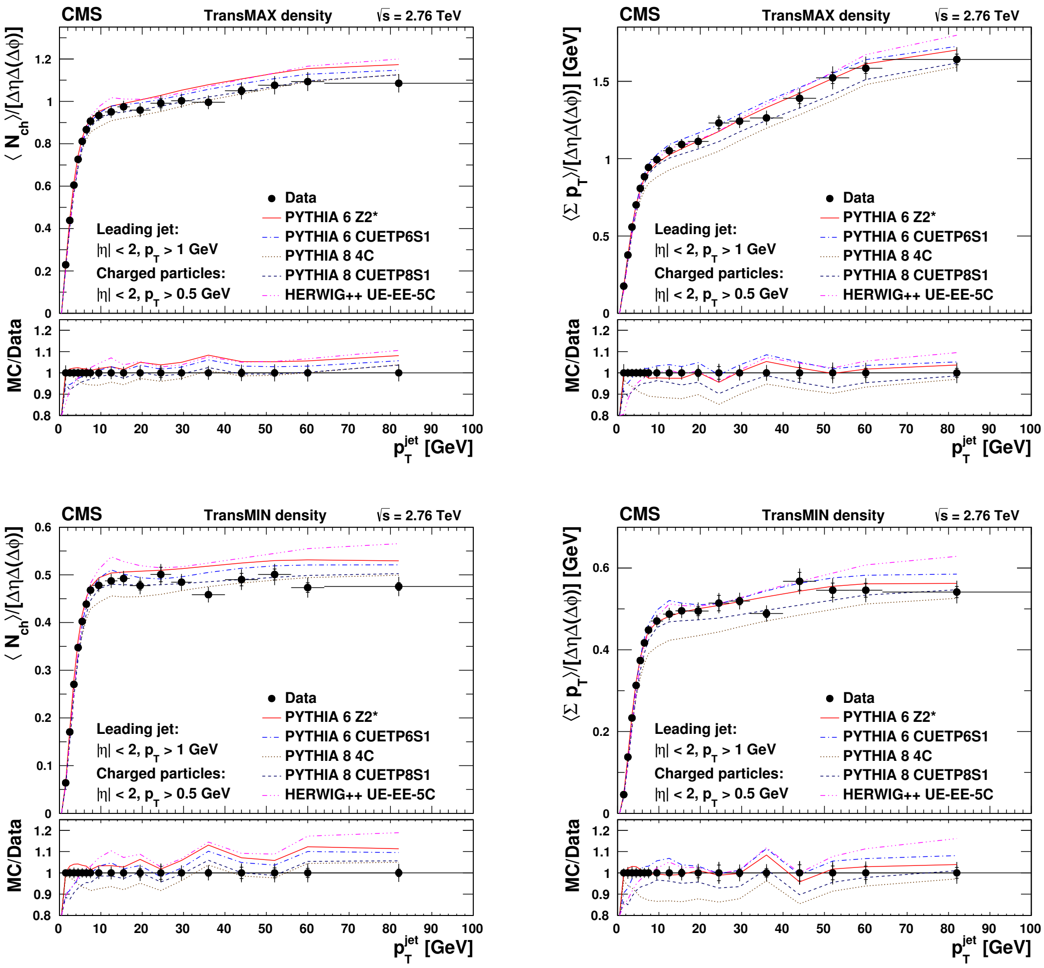

Figure 2. Measured (left panes) particle density, and (right panes) Σp_{T} density, in the transMAX and transMIN regions ($60^\circ < |\Delta\varphi| < 120^\circ$, relative to the leading charged-particle jet in the event, with maximum/minimum UE activity), as a function of $p_{\mathrm{T}}^{\mathrm{jet}}$. The definitions of the symbols and error bars are the same as for figure 1.

contributions of QCD radiation from the hardest scattered partons. The same trend is observed in $\mathrm{p\bar{p}}$ collisions at 1.96 TeV [3]. The latest PYTHIA6 (PYTHIA8) tune CUETP6S1 (CUETP8S1) improves the description of the data in comparison to the results obtained with the parameters of the previous Z2* (4C) tune.

The centre-of-mass energy dependence of the UE activity in the transverse region is presented in figure 4 as a function of $p_{\mathrm{T}}^{\mathrm{jet}}$ for $\sqrt{s} = 0.9$, 2.76, and 7 TeV [4, 5]. A fast rise with increasing centre-of-mass energy of the activity in the transverse region is observed for the same value of the leading charged-particle $p_{\mathrm{T}}^{\mathrm{jet}}$. This is expected from the higher parton densities probed at low-x in the protons, and the larger phase space available for parton radiation. All tunes predict a centre-of-mass energy dependence of the UE activity which is consistent with that of the data.

The measurements presented here provide constraints for the development and tuning of the underlying event description implemented in MC models. In particular, they may

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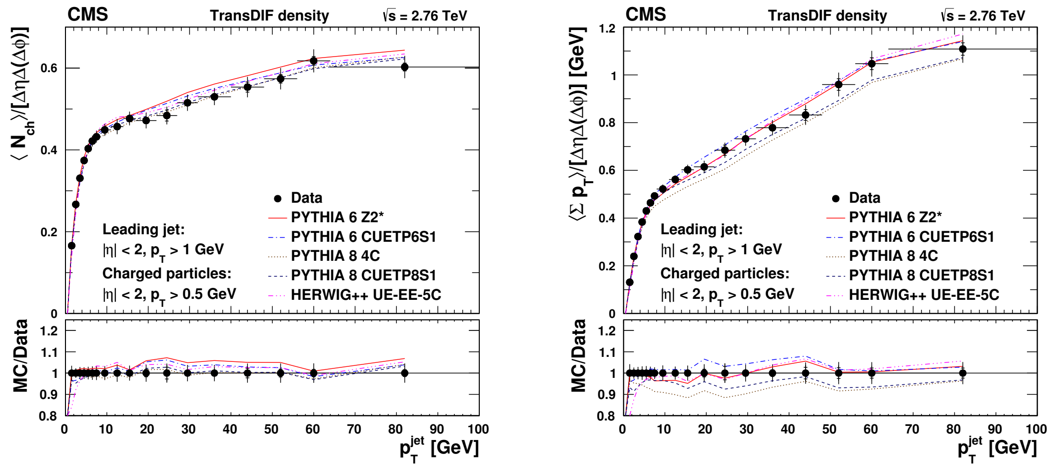

Figure 3. Measured transDIF activity (see text for its definition) for (left) particle density, and (right) Σp_{T} density, as a function of $p_{\mathrm{T}}^{\mathrm{jet}}$. The definitions of the symbols and error bars are the same as for figure 1.

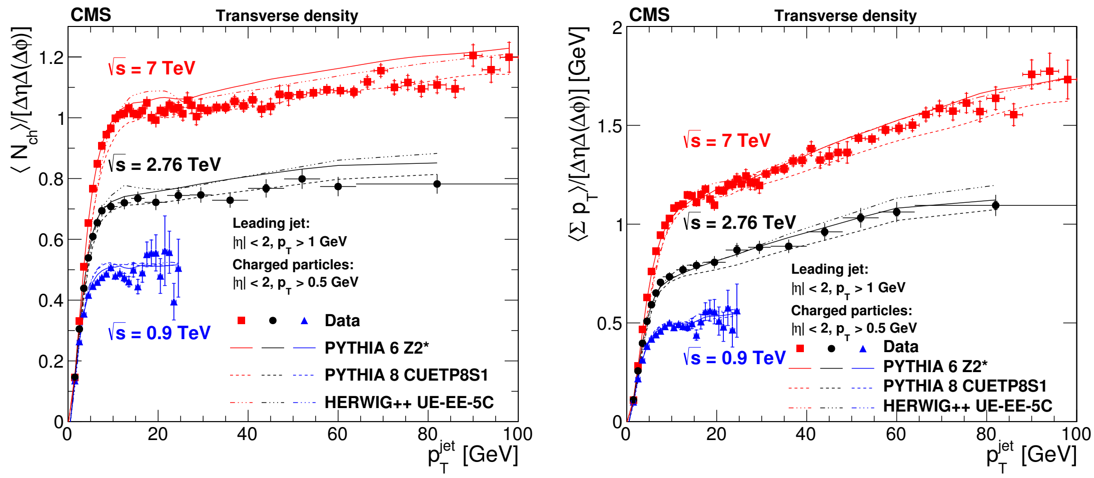

Figure 4. Comparison of UE activity at $\sqrt{s} = 0.9$, 2.76, and 7 TeV for (left) particle density, and (right) Σp_{T} density, as a function of $p_{\mathrm{T}}^{\mathrm{jet}}$ [4, 5]. The data (symbols) are compared to various MC simulations (curves). The definition of the error bars is the same as for figure 1.

allow improving the modelling of key ingredients — such as multiparton interactions, QCD radiation, energy evolution of the transverse proton profile, etc. — which will play an increasing role at higher proton-proton collision energies.

5 Summary

The measurement of the underlying event (UE) activity in proton-proton collisions at $\sqrt{s} = 2.76$ TeV has been presented using events with a charged-particle jet produced at central pseudorapidity ($|\eta^{\mathrm{jet}}| < 2$) with transverse momenta $1 \leq p_{\mathrm{T}}^{\mathrm{jet}} < 100$ GeV. This analysis complements the results of previous similar measurements at $\sqrt{s} = 0.9$ and 7 TeV.

The UE activity is measured in the transverse region and further studied in terms of the transMAX, transMIN and transDIF activities. A steep rise of the underlying activity in the transverse region is seen with increasing leading jet p_{T}. This fast rise is followed by a leveling above $p_{\mathrm{T}}^{\mathrm{jet}} \approx 8\,\mathrm{GeV}$, with nearly constant particle density and small Σp_{T} density increase. Such a distinct pattern (fast rise followed by a leveling of the UE hadronic activity) is clearly seen for all the observables in the various regions, and is compatible with the impact parameter picture of pp collisions featuring an increasing number of MPI for increasing overlap followed by a saturation of hadron production once the hardest most-central collisions are reached. The transDIF density distributions show an increase of the activity as a function of $p_{\mathrm{T}}^{\mathrm{jet}}$, corroborating the hypothesis of more intense ISR and FSR from the increasingly harder parton-parton scatter.

The results are compared to recent tunes of PYTHIA and HERWIG++ Monte Carlo event generators. The PYTHIA6, PYTHIA8, and HERWIG++ tunes describe the data within 5 to 10%. All MC tunes predict a collision energy dependence of the hadronic activity similar to that observed in the data. The ability of the latest Monte Carlo generator tunes to describe the data confirms the validity of the tunes and lends confidence to the predictions of UE activity for higher collision energies.

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